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The optical filter of the disk chopper spectrometer at NIST

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Abstract

The Disk Chopper Spectrometer at the NIST Center for Neutron Research (NCNR) uses a "neutron optical filter" to remove high-energy neutrons and gamma rays. Nevertheless the measured background at the sample position is time-dependent because of short-wavelength neutrons that get through the optical filter and the choppers. We explain how this happens.

Keywords: Neutron optical filter; Time-of-flight spectrometer

A time-of-flight spectrometer, known as the Disk Chopper Spectrometer (DCS) [1], has been installed on neutron guide NG4 at the NCNR. Since the guide is straight, and the sample position is in line with the guide at its exit, a means was sought to remove high-energy neutrons and gamma rays from the beam. Had we only wanted neutrons with wavelengths $\lambda > 4$ Å (1 Å $= 0.1$ nm) we would have used a cooled beryllium filter. Since this was not the case we decided to use a "neutron optical filter" [2,3]. Resolution considerations dictated that we could at most use a ≈ 30 mm wide beam and since the initial width of the guide is 60 mm we concluded that the design shown in Fig. 1 was reasonable. Fig. 2(a) shows its "transmission efficiency" (see below) at short wavelengths, according to Ref. [3]. After the optical filter there is an additional ≈ 10 m of guide and a set of seven disk choppers. The absorbing material on each disk is plasma-sprayed $^{nat}Gd_2O_3$; the reported surface number density of Gd atoms, ρ_{Gd}, is 3.5–3.8 $\times 10^{20}$ cm^{-2} so that the theoretical transmission for 1 Å neutrons is between 0.0039 and 0.0065. In the course of measurements to characterize the beam leaving the guide we found that the background was time-dependent (Fig. 3). Spectra obtained with a detector placed at different distances from the final chopper unequivocally showed that the background mostly comes from neutrons with $\lambda \approx 0.55$ Å. In seeking to understand why such neutrons are present in the guide, we have discovered two matters that were overlooked or ignored in the original calculations [3].

(1) In Ref. [3] it was assumed that "the first and last sections [i.e. the parallel sections before and after the tapered section (see Fig. 1)] are sufficiently long that a neutron can only get through the section if the angle between the neutron's trajectory and the axis of the section is no greater than the critical angle of the section". The assumption is fully justified for the final section of the NG4 filter but not for the first section, for which the condition is $\phi_1 \leqslant \theta_c$ where θ_c is the critical angle and ϕ_1 is

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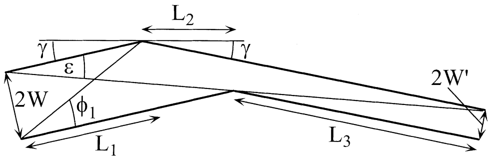

Fig. 1. The NG4 optical filter, viewed from above; $L_1 = 12000$ mm, $L_2 = 6876$ mm, $L_3 = 25325$ mm, $2W = 60$ mm, $2W' = 30$ mm, $\gamma = 0.125°$, $\varepsilon = 0.182°$, $\phi_1 = 0.286°$.

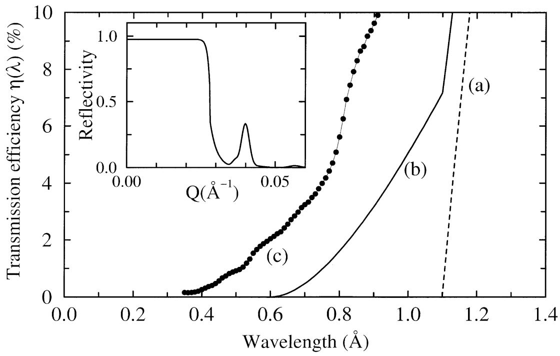

Fig. 2. (a) The theoretical transmission efficiency $\eta(\lambda)$ of the NG4 filter, from Ref. [3]. (b) The complete theoretical $\eta(\lambda)$, as given in the text. (c) The results of a ray-tracing calculation of $\eta(\lambda)$ using the measured reflectivity shown in the inset; $Q = (4\pi/\lambda)\sin\theta$.

the divergence angle (Fig. 1). If the critical angle is 0.002 rad/Å (0.115°/Å) the "sufficiently long" assumption only holds for $\lambda > 2.5$ Å.

The most instructive way to characterize the performance of the NG4 optical filter is to study its "transmission efficiency" $\eta(\lambda)$, defined as $I_F(\lambda)/I_\infty(\lambda)$ where I_F is the intensity at the guide exit and I_∞ is the intensity at the exit of an infinitely long straight guide with the same exit width, whose reflectivity $R(\theta)$ (where θ is the angle between a neutron's trajectory and the guide surface) is a step function with $R = 1$ for $\theta \leqslant \theta_c$, $R = 0$ otherwise. Since $\eta(\lambda)$ is a ratio of intensities we ignore quantities common to I_F and I_∞. We write I_F as the sum of $I_{F,1}$, the intensity due to neutrons reflected within the first section, and the remaining intensity $I_{F,2}$; $I_{F,2}$ was omitted from the treatment given in Ref. [3]. We obtain $I_{F,1} = 0$ for $\theta_c \leqslant \gamma$, $3(\theta_c - \gamma)W$ for $\gamma \leqslant \theta_c \leqslant 2\gamma$, $2W\theta_c - W(\theta_c - 4\gamma)^2/4\gamma$ for $2\gamma \leqslant \theta_c \leqslant 4\gamma$, and $2W\theta_c$ for $4\gamma \leqslant \theta_c$; $I_{F,2} = 0$ for $\theta_c \leqslant 2\gamma - \varepsilon$, $(\theta_c + \varepsilon - 2\gamma)^2(L_1 + L_2)/2$ for $2\gamma - \varepsilon \leqslant \theta_c \leqslant \gamma$, $(\theta_c - \varepsilon)^2(L_1 + L_2)/2$ for $\gamma \leqslant \theta_c \leqslant \varepsilon$, and 0 for $\varepsilon \leqslant \theta_c$; γ and ε are shown in Fig. 1. By definition $I_\infty = 4W'\theta_c$. Fig. 2(b) shows the complete theoretical $\eta(\lambda)$; because of $I_{F,2}$ there is intensity at wavelengths < 1.1 Å.

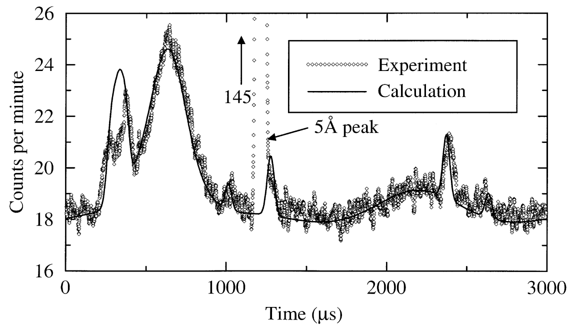

Fig. 3. A time-of-flight spectrum recorded using a ^{3}He detector placed 760 mm from the final DCS chopper. The choppers, operated at 20000 rpm, were phased to transmit 5 Å neutrons in the "low-resolution" mode [1]. Boron glass, with transmission $T_B(\lambda) \approx \exp(-1.09\lambda[\text{Å}])(\approx 0.43\%$ at 5 Å), was placed in the beam to avoid detector saturation due to the 5 Å neutrons. The result of an analytical calculation is also shown.

(2) The assumption that $R(\theta)$ is a step function is a reasonable first approximation if the guide coating is ^{58}Ni, particularly if R is allowed to be slightly less than unity for $\theta \leqslant \theta_c$. In actual fact the vertical faces of the NG4 guide are coated with ^{58}Ni-equivalent supermirror material and since the "critical angle" of the supermirror material is not much greater than that of natural nickel few supermirror layers are required. Hence $R(\theta)$ has significant structure above θ_c. Using the measured reflectivity, shown in Fig. 2, we have calculated $\eta(\lambda)$. Once again η is enhanced at short wavelengths (Fig. 2(c)).

Having discussed why there are short wavelength neutrons in the guide we shall now describe our explanation of the observed spectra. Fig. 3 shows a typical spectrum. Apart from the 5 Å peak (at ≈ 1200 μs) there is clearly a background with considerable structure. Similar background spectra were obtained with other chopper phasings. We write the detector count-rate as

$$N(t) = \int \Phi(\lambda) \prod_{k=1}^{7} T_k(\lambda, t - D_{kD}\lambda m_n/h)\, T_B(\lambda) e(\lambda)\, d\lambda$$

where $\Phi(\lambda)$ is the intensity of neutrons of wavelength λ before the first chopper, k labels the choppers, $T_k(\lambda, t)$ is the transmission of chopper k at time t, D_{kD} is the distance from chopper k to the detector, m_n is the neutron mass, h is Planck's constant, $e(\lambda)$ is the detector efficiency, and $T_B(\lambda)$ is explained in the caption to Fig. 3. When chopper k is closed $T_k = T_{Gd}(\lambda) \equiv \exp[-\rho_{Gd}\sigma_{Gd}(\lambda)]$ where σ_{Gd} is the total cross section per atom of Gd; when chopper k is open $T_k = 1$. To the extent that $\Phi(\lambda)$ is known $N(t)$ can be calculated but a simplified calculation is more revealing.

If the choppers are randomly phased a good estimate of the average probability that a neutron will get through the seven choppers, having encountered n open slots, is

$$P_n(\lambda) = \{7!/[(7-n)!n!]\}\, p^n(1-p)^{7-n}[T_{Gd}(\lambda)]^{7-n},$$

where $p = 0.05$ is the average probability of finding a chopper slot open. The total probability $P_{tot}(\lambda) = \sum P_n(\lambda)$ decreases rapidly with increasing λ, falling to 1% at $\lambda \approx 0.66$ Å. Furthermore $(P_0 + P_1)/P_{tot}$ ranges from $\approx 96\%$ at very short wavelengths to $\approx 86\%$ at $\lambda \approx 0.66$ Å. Thus a calculation that ignores neutrons that passed through more than one open slot should suffice. The intensity at the detector at time t, $I_0(t)$, *for neutrons of a single wavelength* λ_0, is approximately proportional to

$$1 + \frac{1 - T_{Gd}(\lambda_0)}{T_{Gd}(\lambda_0)} \times \sum_{k,j} R[\delta_{kj}/\omega, \mathrm{mod}(t - D_{kD}\lambda_0 m_n/h, 2\pi/\omega)]$$

where $R(\Delta, x) = 1$ when $|x| \leqslant \Delta/2$ and 0 otherwise, δ_{kj} is the angular width of slot j in chopper k, and ω is the angular frequency of the choppers. Since P_{tot} and T_B decrease with increasing λ but Φ and e have the opposite behavior, the distribution of wavelengths responsible for the background should be quite narrow, in agreement with direct observation. Assuming a Gaussian distribution centered at λ_0 with standard deviation σ_λ, $I_0(t)$ must be convoluted with a Gaussian in time, whose standard deviation is $D_{kD}\sigma_\lambda m_n/h$. Good agreement with experiment (for a variety of chopper phasings) is achieved using $\lambda_0 = 0.55$ Å and $\sigma_\lambda = 0.10$ Å (e.g. Fig. 3). With $T_{Gd} = 0.8$ (which is reasonable) the calculations also account for the *time-independent* component, implying that almost all of the background is probably due to neutrons within this small range of wavelengths.

In the short term, when circumstances warrant, we shall correct for effects due to the time-dependent background, measuring it by placing an appropriate thickness of Gd_2O_3 in the beam. If and when it proves necessary to suppress the background permanently we shall explore our options.

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